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GEOMETRY OPTIMIZATION OF ARCHED STONE STRUCTURES UNDER GRAVITY AND SEISMIC TYPE LOADINGS

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Abstract

The rapid evolution of technology in recent years has catalyzed many areas of human activity. The computer has become an integral part of everyday life and an important tool in civil engineering, thus allowing the engineers to give quickly and accurately solutions in plethora of complicated problems. In the present manuscript the modeling and topological optimization of arched stone structures consisting of individual parts using FEM was carried out. The imposed loading conditions consist of both gravity and seismic type actions. Topological optimization becomes an original process for the profession of civil engineering. The focus of the study is to propose a new methodology of designing structures verifying the optimal angle of the interfaces among the different stone parts of the arch. Through the process of this optimization the reduction the demanded material, leading to the reduction of the total weight of the arched structure is also investigated. Through the proposed methodology the most techno-economical and most durable solution is prevailed. The optimized design resulted in over 50 percent decrease of the existing mass of the arched structure. Finally, the manuscript discusses the feasibility of constructing these optimized structures utilizing AM technology.

Keywords: Topology Optimization, Arch stone structures, Sustainability, AM technology

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1 INTRODUCTION

The concept of topological optimization and 3D printing of structures is something new to the construction industry. Romain de Laubier et.al believe that 3D printing technology is directly linked to the development of the construction industry and that one day structures will be printed out mechanically without human intervention [1]. There are already several approaches to the method of printing structures made of concrete, clay or even mortars with the equivalent mechanical properties of stone. These methods are described by C. Gosselin et.al. and R. Duballet et.al. who comprehensively outline the process of printing 3D concrete structures [2, 3]. Nathalie Labonnote et.al. make an extensive account of 3D printing for civil engineering projects and give examples of projects that have already been printed, such as in the Netherlands, China, etc. [4]. However, 3D printing is not limited to buildings - similar efforts have also been made regarding bridges. For example, Theo A. M. Salet et.al. constructed a fully functional bicycle bridge [5] while Gieljan Vantyghem et.al. modelled and laboratory-tested a topologically optimised simply supported beam [6].

3D printing is a very valuable process for the construction industry of 3D geometries. S.Lim et. al. Demonstrate methods for the printing of large composite concrete structures [7]. It is based on the principle of sequential addition of material in order to achieve the final defined geometry. The first references to it were made around the 1980s. n recent years, however, it has become better known due to the rapid growth of the use of the computer in the design of these geometries. As mentioned by G.Allaire et.al. [8] there are two main stereolithography techniques, also known as 3D printing:

- (Material extraction methods) Methods based on the depositing of material from a hole over the previous material which is bound with it while being deposited. The majority of applications are printed using this method. Examples describing the methodology but mainly the composition of cement mortars are by W.R. Leal da Silva et.al. [9] and Freek Bos et.al. [10].
- (Powder bed fusion) Methods are based on spraying powder at the beginning and then fusing it using a laser or an electrode. Dirk Lowke et.al. demonstrate that this technique opens new horizons in terms of both mechanical strength and architectural design of the structure [11].

With the help of 3D printing any geometry can be printed which allows the civil engineer to optimize the geometries in his/her constructions according to their form. Jikai Liu et.al. in their article analyzes the prospects of topological optimization for 3D printing [12]. Matthijs Langelaar, in addition to creating an optimization method, demonstrates how complex geometries can be built with 3D printing [13]. James J.Kingman et.al. present several topologically optimized structures [14]. In summary, in the last few years many successful works printed by 3D printing have been presented such as the article by Kurt Maute et.al. [15]. Topological optimization is a method used to find the optimal geometry of a given cross section. This depends on the loads from the dimensions as well as the load conditions. Oded Amir and Emad Shakour in their article perform optimization on a pre-stressed concrete beam [16]. Topological optimization is done by several methods which will not be described here. Briefly, there are direct methods, divided into direct and stochastic methods, and indirect methods. Ole Sigmund and Kurt Maute in their article [17] as well as Xia Liu et.al. [18] present in more detail many of the methods and algorithms of optimization. The extension of topological optimization is the schematic optimization where it works complementary to the first one by moving the walls of the geometry to be as optimal as possible.

The construction industry has a major environmental impact, thus creating a demand for sustainable alternatives. In particular, as cited by Agusti-Juan and Habert, the construction industry is responsible for 40% of global energy consumption, 12% of global drinking water disposal, 28% of global greenhouse gas (GHG) emissions and 40% of solid waste production in developed countries [19, 20, 21]. 3D printing technology is gaining ground in the competitive construction industry, on the path to a sustainable future, thanks to the advantages it offers over traditional manufacturing methods. Topological and schematic optimization are tools in the hands of the Civil engineers in order to find the optimal cross-section and eliminate excess material from it [21]. It can be perceived that by optimizing the construction, material reductions of up to 50 percent can be achieved [22, 23]. With the 3D printing technologies and more specifically with the method of topological optimization, the cost and time of construction is minimized due to the reduced materials required, the requirement of less manual labour and at the same time a safer working environment is achieved. In addition to the smaller amount of materials used compared to traditional construction, thus reducing construction waste and the amount of dust, 3D printing technology offers the possibility of using recycled and more ecological construction materials [24, 25, 1]. According to Weng et al. who presented a comparative study of prefabricated bathrooms using 3D printed concrete technology versus the conventional concrete construction method, the results indicated a 25.4% reduction in cost, 85.9% reduction in CO2 carbon dioxide emissions and 87% less energy consumption, resulting in a 26% reduction in weight and 48% increase in productivity [26, 24]. 3D printing of structures is an efficient and cost-effective method with a reduced environmental impact while offering limitless architectural possibilities with the creation of complex geometries and is thus a cornerstone in the development of sustainable construction [25, 27, 20].

However, the 3D printing process has some disadvantages in regard to printing, for example methods based on material deposit cannot easily print structures with large openings according to G.Allaire et.al. [8], as well as high-body structures due to issues with out of plane buckling. R.J.M. Wolfs et.al. created a reliable numerical simulation that can accurately forecast off-plane buckling for freshly printed concrete [28]. In order to print these geometries, special supports are needed during the printing process. While powder printing methods due to the high temperatures generated during powder bonding create residual stresses, G.Allaire et.al. [8].

To overcome the problems of 3D printing mentioned above for civil engineering structures in this article a method is proposed. This originates from the long past of the 1st century BC where it evolved and was largely applied in the Middle Ages. Arched structures have been balanced for thousands of years using simple laws of engineering. The structural stability of arched structures is based on friction and its own dead weight. The static properties as well as the evolution of these structures have been addressed by several people. For example, Albert Samper et.al [29], Santiago Huerta [30], Po-Hung Liu and Chin-Wei Chen, [31]. Some of these structures are in operation even today. Articles detailing and analysing the strength of such bridges are by Paul J. Fanning and Thomas E. Boothby [32] and Tamas Forgacs et.al. [33]. In accordance with this, the structures will be fragmented into smaller sections which will be joined together in the same way as arched structures. This is the subject of a paper by Mario Deuss et.al. [34]. These components will be optimised to reduce their weight, then printed and ultimately assembled.

2 MATERIALS AND METHODS

2.1 Equilibrium mechanism of self-support structures

Self-supporting structures are a complex assembly of smaller parts. The structural integrity of these parts is affected from the compressive forces between these individual pieces. The area of interface between these pieces that has compressive stresses named active area. To achieve the compressive behaviour over most of the tangential plane the methodology of stereotomy and inverse chain is followed. Stereotomy is a process in which randomised blocks are dissected and given a suitable geometry to become part of the curved arc. These pieces are called voussoirs. The first to apply this methodology was Philibert Delorme in his work "Premier Tome de l'Architecture".

In Greece, the craftsmen of Epirus who built great arched structures studied completely through empirical observation. The same way was used in the rest of the world where in the 17th century the method of inverted chain with weights was developed. This discovery was made by Hooke in 1675. That is, he suggested that an arched structure balances like an inverted chain loaded with weights. In this simple way, the geometry and statics of an arched structure were being analysed. More specifically, a chain hanging with the corresponding weights of the vaulted structures has in its entirety only tensile stresses; the shape it takes does not depict the vector of tensile force at each of its points. Likewise, if this chain remains on this curve and is inverted, an arched structure is created where the vector of compressive stresses is plotted. This curve is called the thrust line. The numerical substance of the above was studied in 1870 by James Clerk Maxwell. He first proposed in a mathematical manner the calculation of the forces between the voussoirs in a vectorial manner. Resulting in the creation of a dynamo-polygon and the construction of the pressure line. These diagrams verified the chain theory and made it possible to apply it to more complex structures.

In this way, the optimal geometry that the arched structure should possess is created. The interfaces between the voussoirs are then cut perpendicular to the piezometric line to achieve the largest surface area to be in compression to develop the maximum possible friction but also to transfer stresses uniformly with the smallest stress concentrations.

Friction and cohesion between the stone and mortar plays an important role in the static capacity of arched structures. Usually, in order to create an initial shear strength -cohesion- a range of mortars are used during assembly. The static strength of the construction is mainly determined by whether the different pieces slide together. There are however more factors as for example, failure of bridge's foundation where they are not considered in this article. The destruction of the bridge because of the abutments movement is a study of G.A. Drosopoulos et.al. [35]

Consequently, the main equation that defines the static sufficiency of an arch structure is Coulumb's law:

$$\tau cr = c0 + \mu * \nu$$

whereas:
τ_{cr} :Critical shear stress value
c_0: cohesion
μ: Coefficient of drag
ν : Compression stress of contact

2.2 Finite elements analysis

The static adequacy of the structures of this study is confirmed with the finite elements method. The method of analyzing a continuous medium with the finite element method is similar to that of matrix analysis. Namely the simulation of the construction with individual ingredients which connect to each other through a finite number of nodes. Due to that there are no physical separations in a continuous structure these are added artificially. Thus, the construction is artificially separated in elements that are connected along their sides and are usually four sided with nodes along their facets called finite elements. These finite elements occupy the entire construction we want to simulate. The sum of all the finite elements constitutes a grid which can be analyzed just as in matrix analysis. For example, in a static analysis based on bordering conditions and applied loads on the construction respective matrices are created based on the equilibrium equations allowing the calculation of the displacement of the finite in amount nodes and sequentially all other stresses and figures.

At a programming level the procedure that is followed by the researcher in order to study a construction in order is as follows:

- The geometry of the construction is designed in a CAD program and a three-dimensional model is created.
- The model is divided into finite elements i.e., the mesh is created, and the resolution type is selected and any remaining data that is required is added. For instance, if it is selected for the model to be solved with statical stressing the data concerning the loads and the boundary conditions must be given. This procedure is done with software called pre-processors.
- When the parameters are ready for the resolution, they are entered in a program which will find the solution to the problem with numerical solutions as described previously. These types of programs are called solvers.

When the solution is finalized, the results must be used in a program called a post processor in order for the engineer to see the results of the analysis.

2.3 Static and seismic loading of the models – support method

It was first verified if the models failed with their own weight. To do this, based on the density, a gravity load was applied which represents the gravity force that applied on the individual pieces of the construction. The model was supported on the foundations with embedding conditions.

After a seismic type of loading was applied on the models. In any structure seismic activity plays a vital role in its static adequacy. A seismic activity or earthquake is a noticeable shake of the earth's surface caused by sudden movement of masses which are connected by seismic waves that transfer the energy of the activity. An earthquake on our planet is usually caused by sudden release of energy stored in the earth's crust. We perceive them on the surface as a part of the energy is transferred there through seismic waves. These waves are transmitted to the crust through oscillations of the sedimentary layers and upon reaching the surface cause the shaking of the ground that we perceive. The seismic waves also cause through their oscillations differential electrical potential in the layers of the crust as they travel through them. In the case of civil engineering the seismic response of structures is usually calculated with the use of pseudo-static methods. These methods are known thusly due to the fact that the analysis of the structures is done by adding one more force. According to Eurocode 8 for importance class II, Ground type A (Rock), damping ratio 5 per cent and for seismic hazard zone II (Epirus), from the equation:

$$Sd(T) = a_g * S * N * 2.5$$

,the maximum spectral acceleration of the spectrum is 0,6g.

The seismic force for load case:

$$G + \psi * Q$$

where G is the permanent loads and Q the temporary loads (there are no temporary loads in the construction models), occurs from the equation:

$$Fb = Sd * M * \lambda$$

where Sd the spectral acceleration M the mass of the structure and λ a reduction factor equal to one for safety reasons. For all three models the seismic analysis is done in two directions inside and outside the plane of the construction. Critical in this instance is the one outside this plane.

2.4 Topology optimization

With the term optimization we mean the improvement of an object as to a specific property. In the exact same way when we refer to topology optimization, we mean the improvement of a part of a construction in terms of some properties for example the reduction of volume or distortions of a construction. With this exceptional instrument it is now possible to conserve materials with great precision and at the same time improve the distribution of stresses within the structure.

The greatest benefit of optimizing in the field of civil engineering is the reduction of the volume of the construction and therefore the used material. As the mass of the structure decreases, the seismic forces acting on it also decrease. Therefore, the cost of the structure is also reduced since there are less seismic forces and less material is used, which costs less. The methodology of topological optimization includes:

- The designer establishes the initial dimensions, i.e., the volume before the optimization process is applied.
- It is then advisable to verify the structure for its staticity before optimization is performed. The forces and boundary conditions for which the geometry will be optimised are defined.
- The areas which the volume and form of the structure must not change are defined.
- The optimization criteria are defined.
- Finally, the construction is optimized.

The methodology outlined above underpins most topological optimization algorithms. These algorithms are mainly divided by the way they work to determine the optimal configuration of the structure. There are two main categories: the direct, divided into causative and stochastic, as well as the indirect.

When a construction undergoes topology optimization or any other form of optimization that is done with some set criteria. In this case of the three models, it was mainly done based on the reduction of volume of the constructions. An important limitation was not to alter the external surface so as not to alter the form given by the architect. In all three cases the volume was removed from the inside out and we have quite a reduction of it. It is important to mention that all three constructions will be printed by a three-dimensional printer with a material of similar properties to that of stone, so we are unaffected from the geometry of the shape for there to be difficulties in the construction. Another less important criteria was that of the reduction of the stress solid.

2.5 Materials Finite elements analysis

In this manuscript, as already mentioned, it is focused on the relative movements between the domes and not on the material of them, so an elastic material was used. The properties of this are shown in the following table.

Stone Density (ton/mm^3)	Young's modulus (MPa)	Poisson's ratio	Friction Coefficient
2.7E-9	50000	0.15	0.6

Table 1: materials of the models

The dimensions of the models that are analyzed and optimized are summarized in the following table.

	First model (mm)	Second model (mm)	Third model (mm)
Height	1100	2550	2330
Width	2400	1800	3280
Thick-ness	300	400	450

Table 2: dimensions of the models

The models are presented below. The first model which is analyzed is a bridge consisting of three individual pieces and relatively simple geometry. The second construction consists of thirteen individual pieces it is an architecturally irregular construction with different geometry and a lack of symmetry. The third and final construction is an architectural arch which is made up of thirteen individual pieces and is curved and so is geometrically more complex.

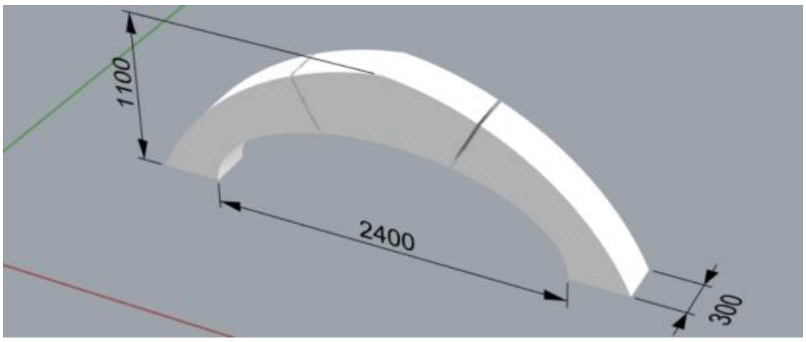

Figure 1: Proportions of the first constructions (in mm)

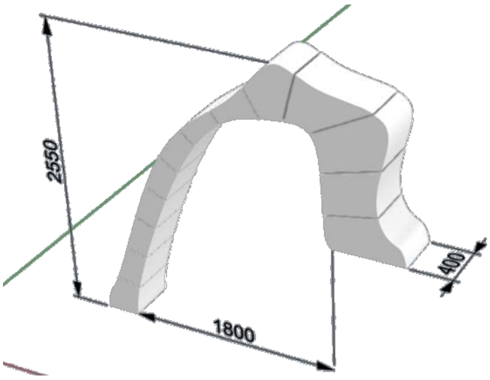

Figure 2: Dimensions of the second construction in millimeters.

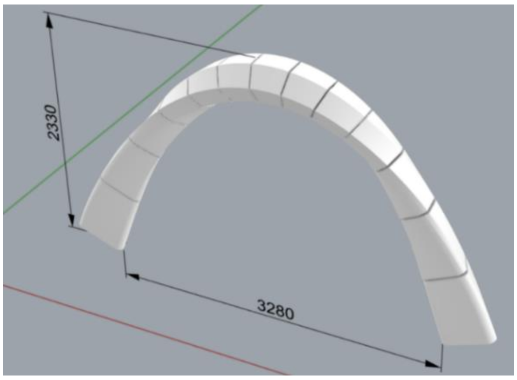

Figure 3: Dimensions of the third construction in millimeters.

3 RESULTS

In this chapter, the results of model analyses are presented from the one that has the simplest geometry to the most complex. The stresses exerted on the individual pieces as well as the maximum displacement is presented. In the first model in the case of self-weight loading there is no form of failure, and the behavior of the construction is as expected. The stresses are in MPa and the displacement in mm.

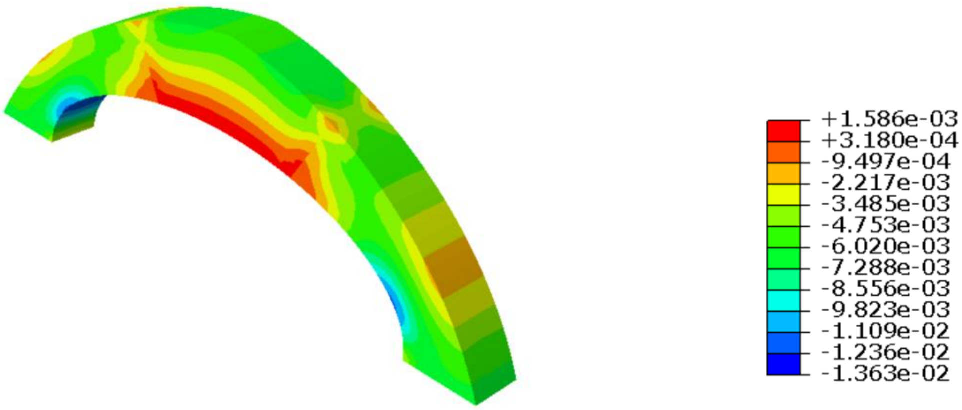

Figure 4: Stresses (MPa)

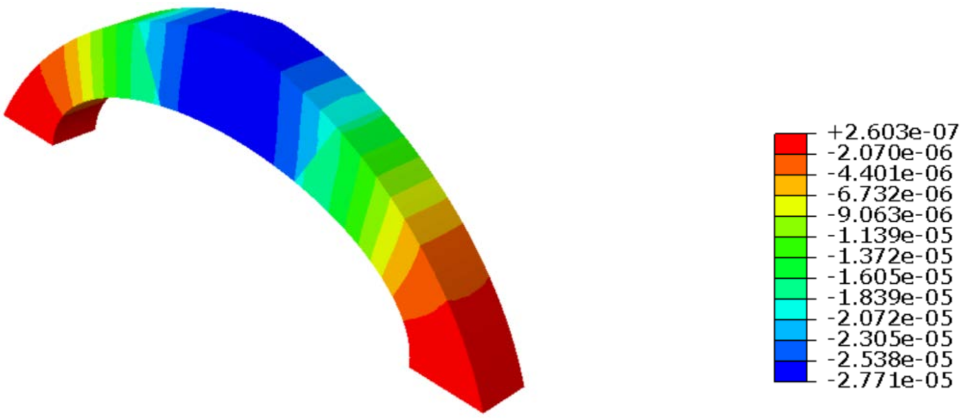

Figure 5: Displacements (mm)

In in-plane seismic loading, large stress concentrations are created between the individual pieces is observed that can lead to the failure of the construction. The results of stress and strain when the seismic activity is within the plane of the construction is depicted below. Stress in MPa and displacement in mm.

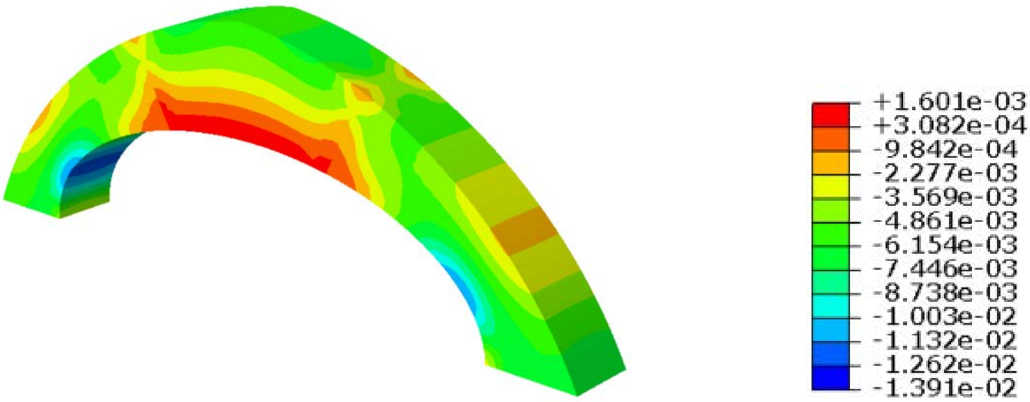

Figure 6: Stresses (MPa)

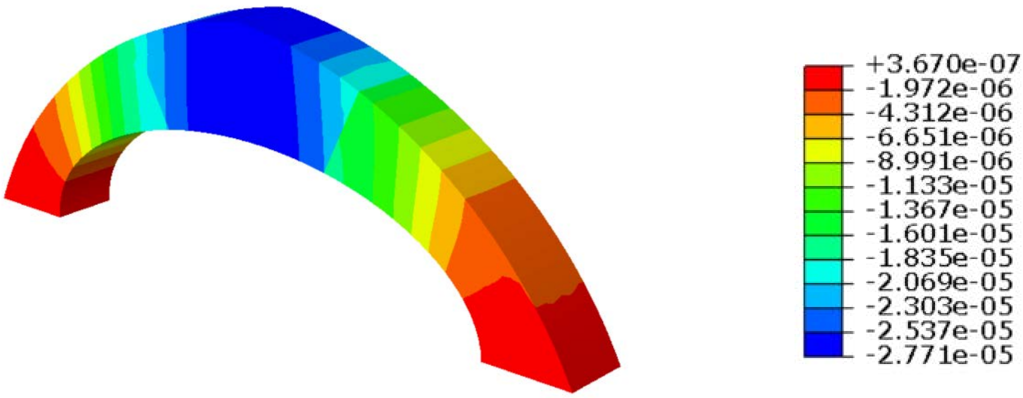

Figure 7: Displacements (mm)

In out-of-plane seismic loading the same behavior is observed. In general, the first structure withstands the seismic loading.

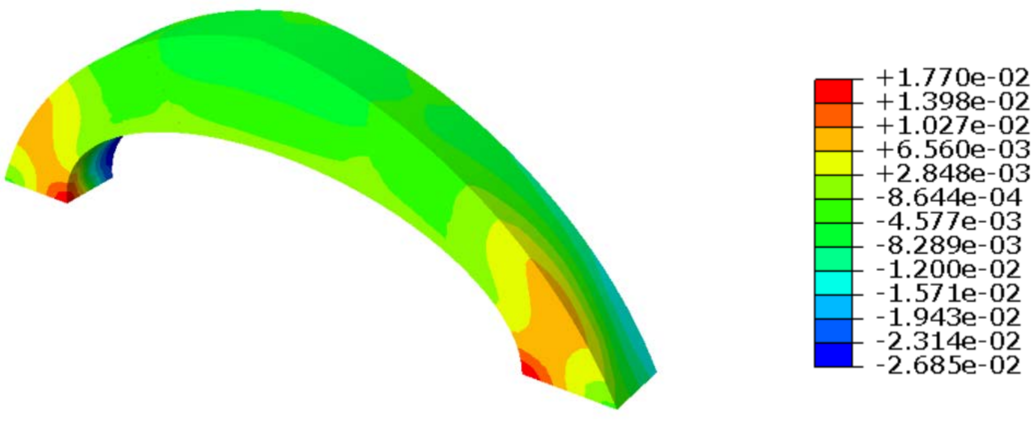

Figure 8: Stresses (MPa)

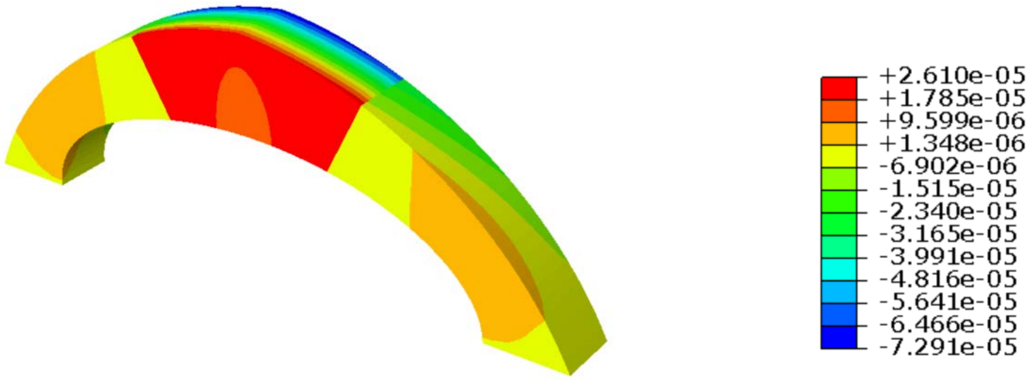

Figure 9: Displacements (mm)

In the second model connecting mortar was used between the individual pieces since without it there was a large amount of slip. It is observed that the more pieces a construction has the stresses between them are better distributed. This is depicted in the next images, where there is compression stresses between the members of the model. Also, there are a small sheer stresses that do not exceed the mortars limit. The results are shown in the figures below. Stresses are in MPa and displacement in mm.

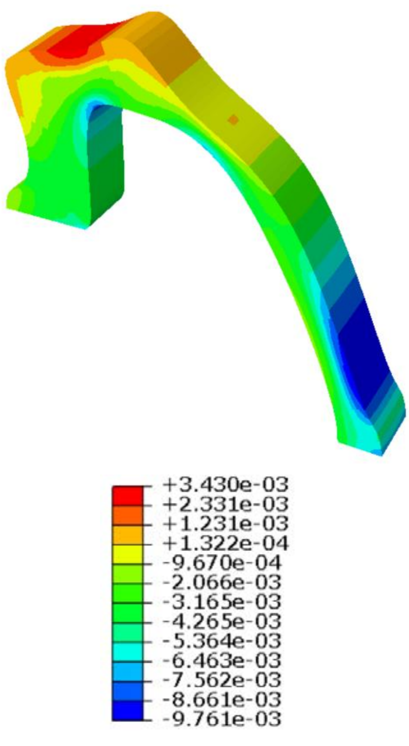

Figure 10: Stresses (MPa)

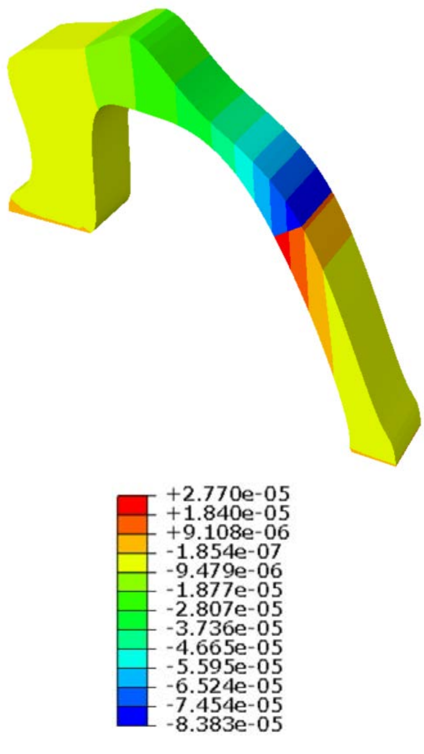

Figure 11: Displacements (mm)

In in-plane seismic loading, we observe that for the second model a collapse does not occur. It is remarkable that due to the smaller interface between the individual pieces they have more slip compared to the rest leading to the creation of a sensitive area of the construction as seen in the figures below. The stresses are in MPa and the displacements in mm.

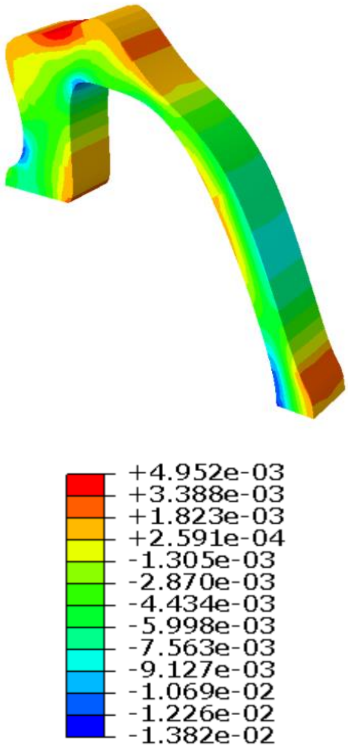

Figure 12: Stresses (MPa)

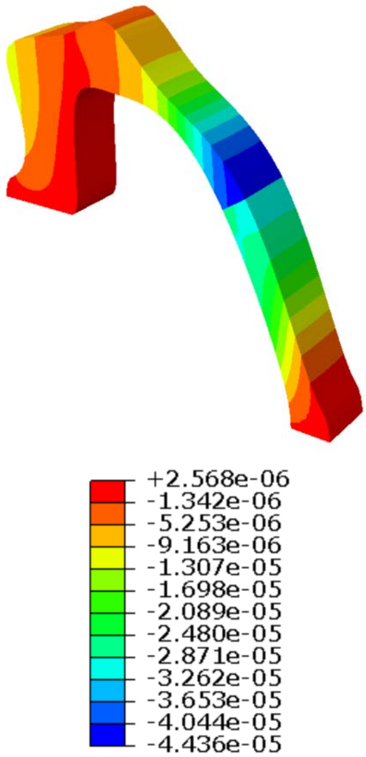

Figure 13: Displacements (mm)

The results for out of plane seismic loading represented below. The static adequacy is confirmed.

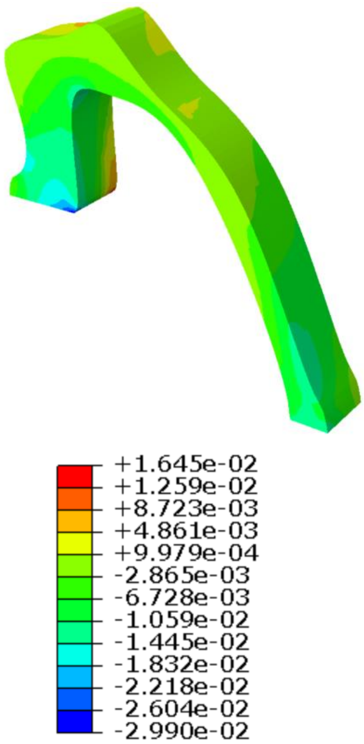

Figure 14: Stresses (MPa)

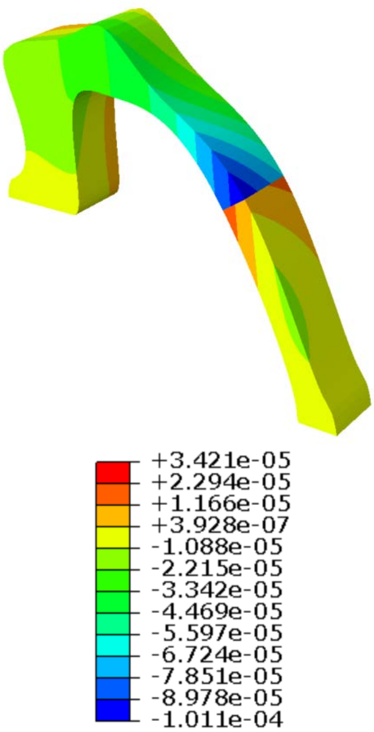

Figure 15: Displacements (mm)

As in the first case the behaviour of the third model is normal with very small slip and below the stresses and deformations of the constructions are shown. Stresses in MPa and displacements in mm.

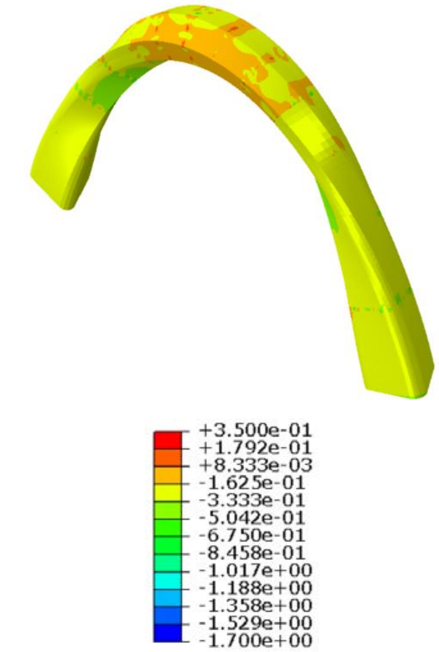

Figure 16: Stresses (MPa)

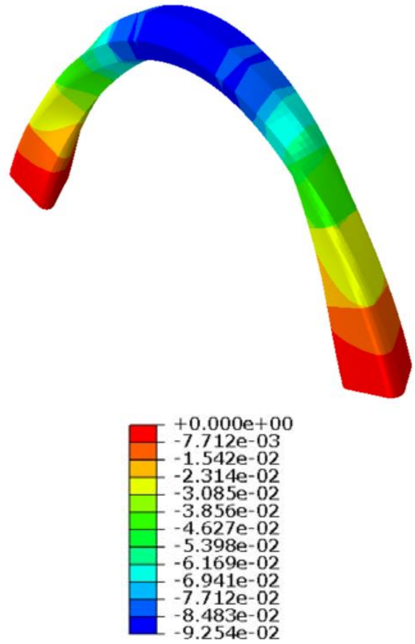

Figure 17: Displacements (mm)

The third construction does not fail when the seismic activity is transferred in the direction of the inside plane

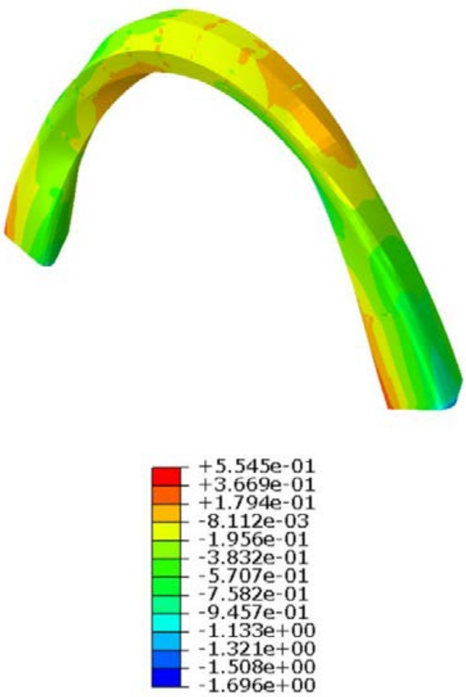

Figure 18: Stresses (MPa)

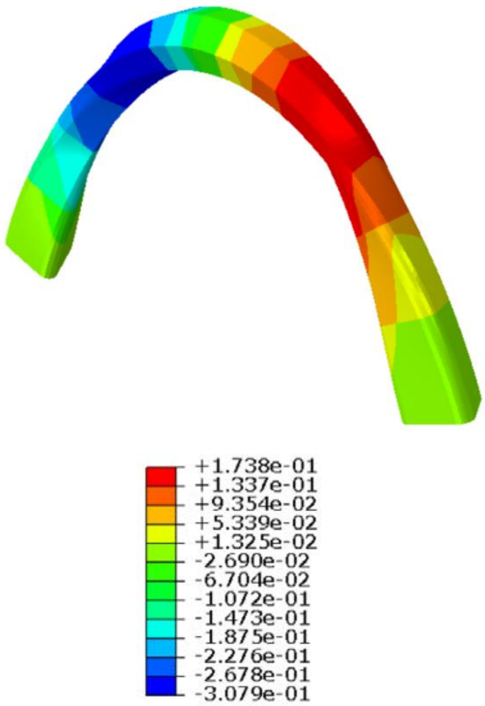

Figure 19: Displacements (mm)

However a large amount of slip is observed when the action is applied on the outside plane. The model appears to fail in the outside plane seismic action so the acceleration is reduced from 0,6g to 0,1g. Presented below the stress and deformation. The stress in MPa and the displacement in mm.

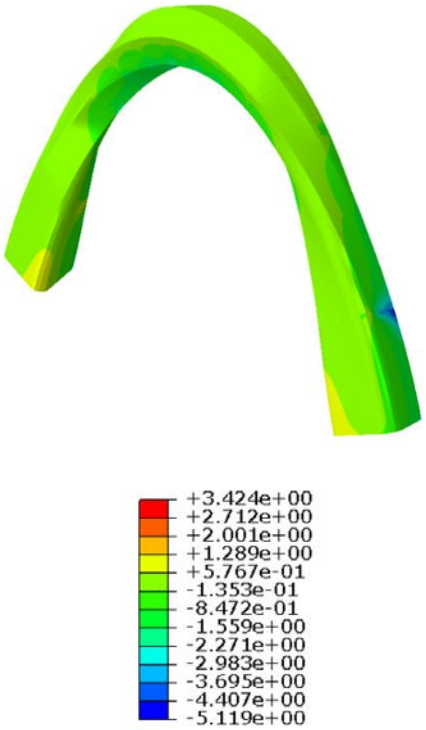

Figure 20: Stresses (MPa)

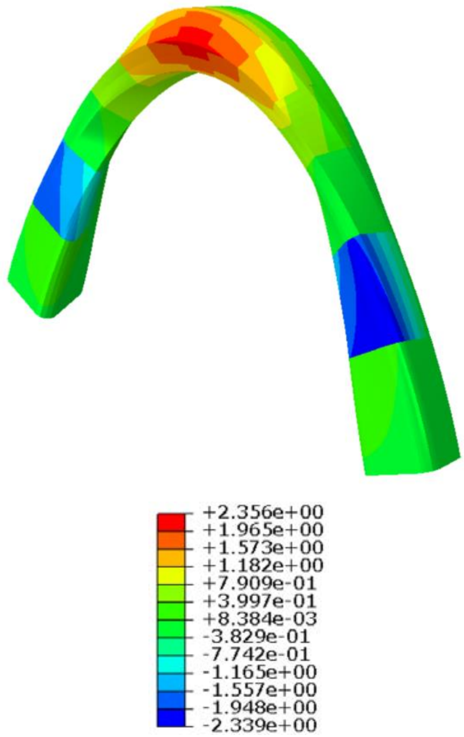

Figure 21: Displacements (mm)

3.1 Topology

The criteria set for the first construction was the reduction of its volume by 25 percent while the stresses remain between 1 to -40MPa. In the end a reduction of the magnitude of 27.25% was achieved while the stress was 0.05MPa. In the following figures the stresses, the deformation as well as the area of the material removed of the optimized construction is shown. The stress in MPa and the displacements in millimeters.

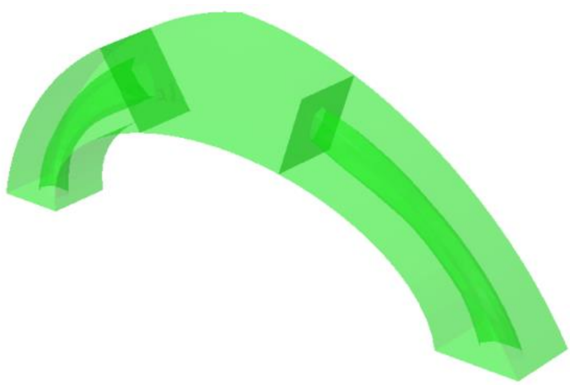

Figure 22: Model after optimization

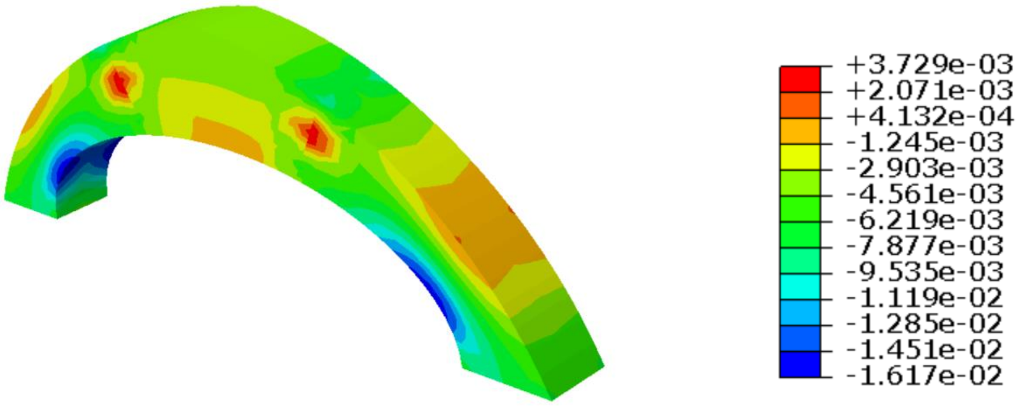

Figure 23: Stresses (MPa)

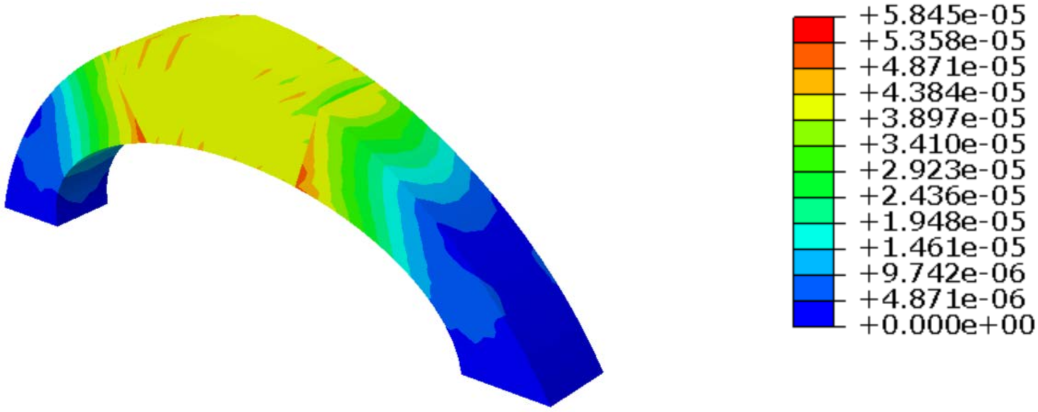

Figure 24: Displacements (mm)

The same criteria set for in-plane seismic load. The model had almost the same volume reduction and behavior with self-weight loading, but the volume reduction happened somewhere else in the models volume.

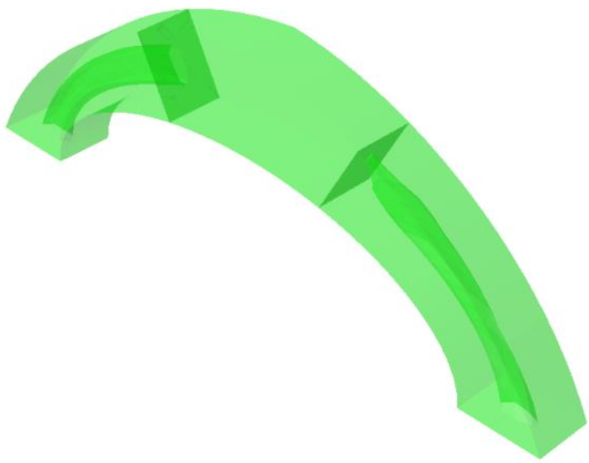

Figure 25: Model after optimization

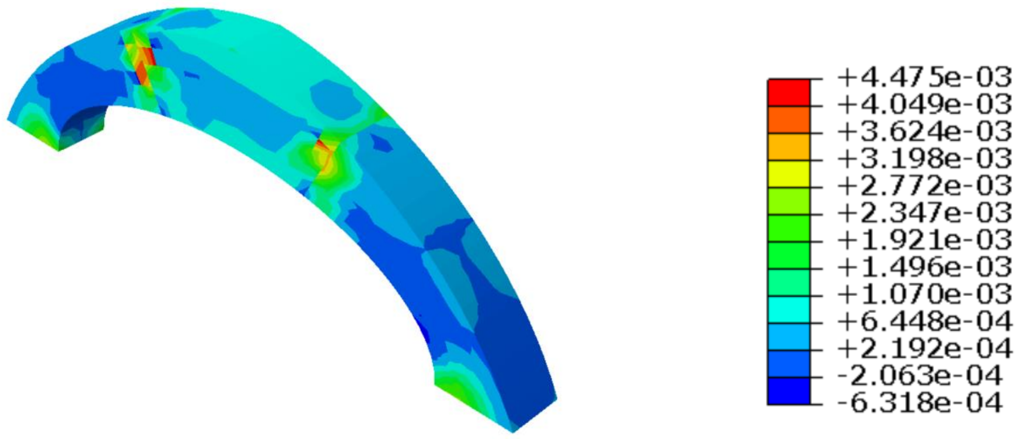

Figure 26: Stresses (MPa)

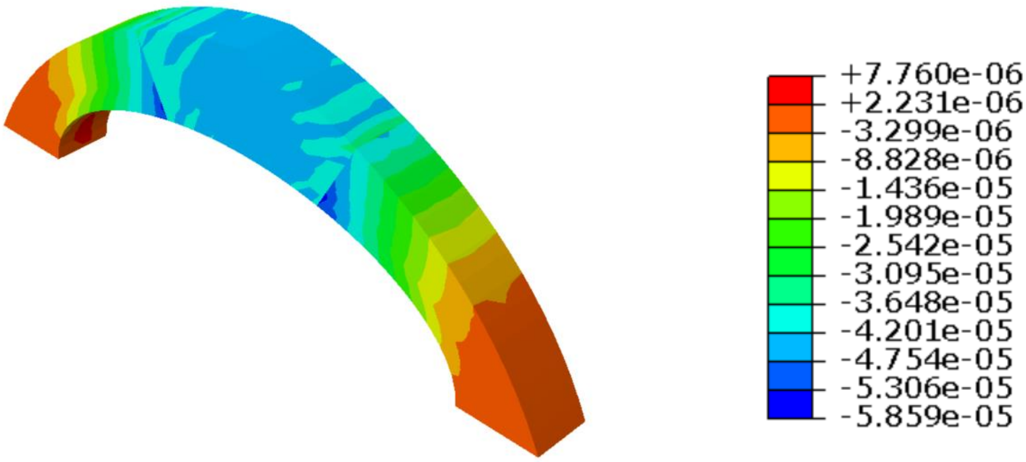

Figure 27: Displacements (mm)

Also out of plane has the same volume reduction. In the following figures the stresses, the deformation as well as the area of the material removed of the optimized construction is shown. The stress in MPa and the displacements in millimeters.

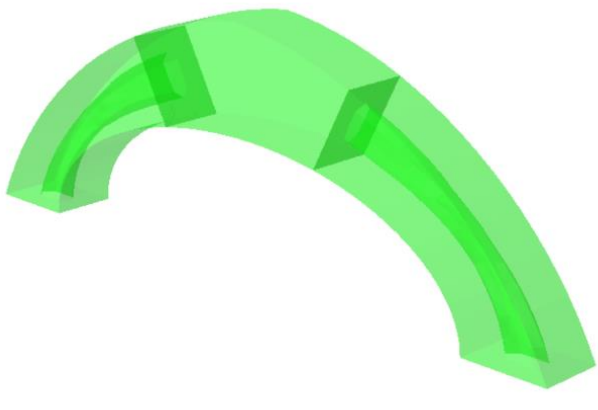

Figure 28: Model after optimization

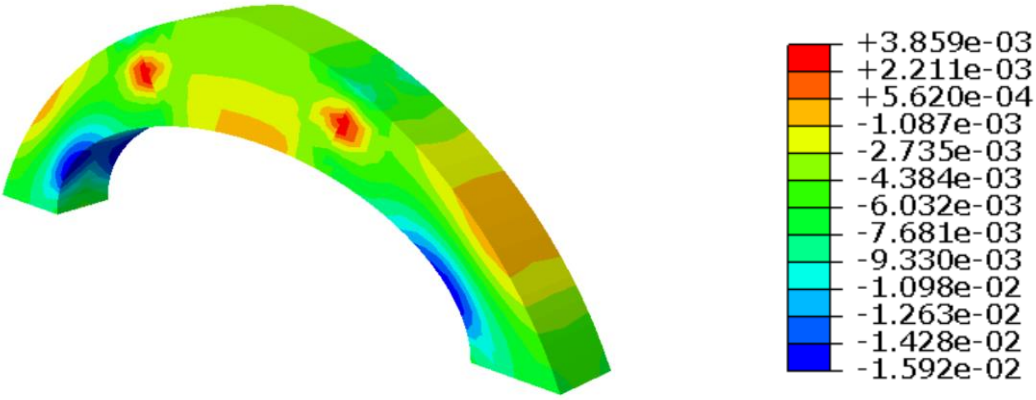

Figure 29: Stresses (MPa)

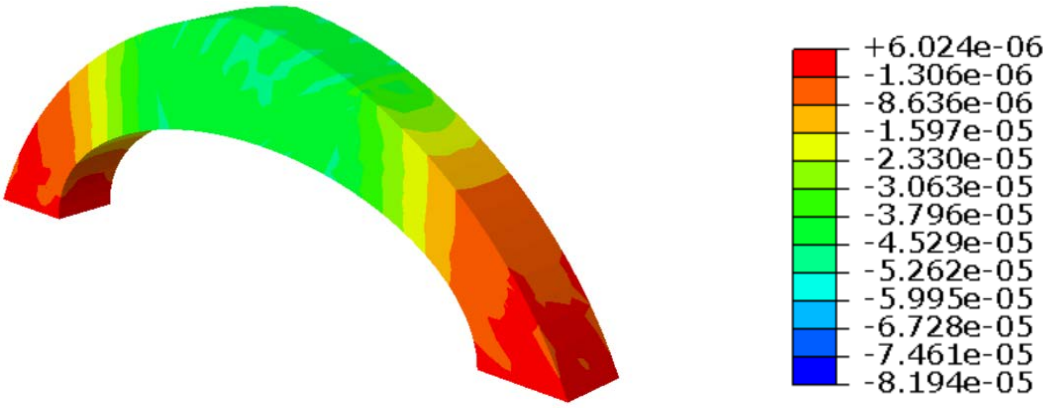

Figure 30: Displacements (mm)

Moving on to the second construction where the reduction of volume was set to 50 percent as well as the stress to not exceed 0 MPa and to be more than -40 MPa. In the end a reduction of volume to the magnitude of 51 percent of the initial volume was achieved and stress was to the scale of 0.09 MPa. Following are the figures of stress and deformation as well as the reduction of volume for the second construction.

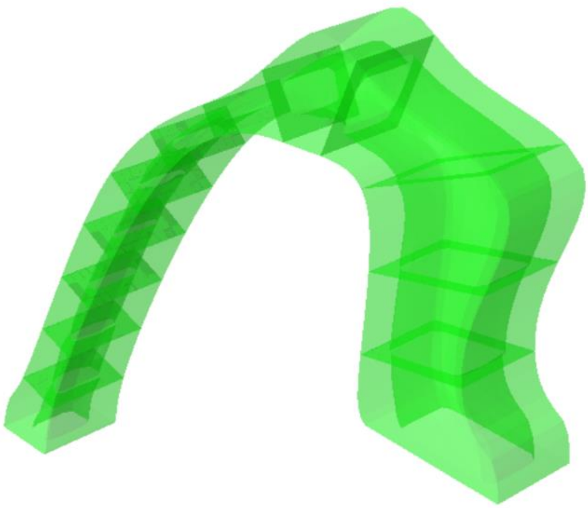

Figure 31: Model after optimization

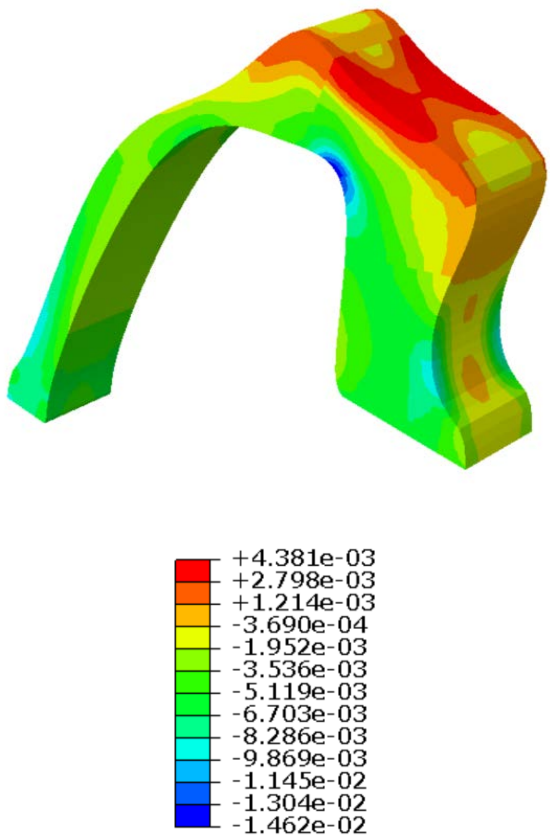

Figure 32: Stresses (MPa)

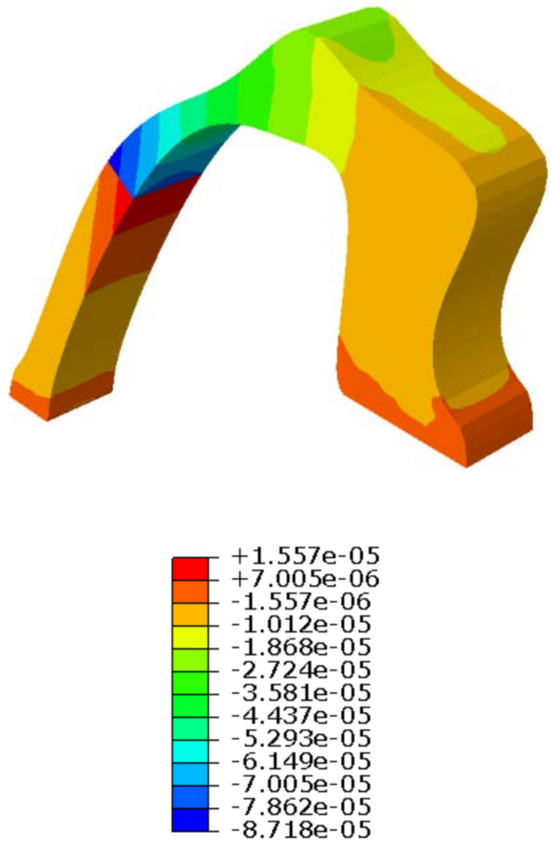

Figure 33: Displacements (mm)

A reduction of 48 percent of the original volume is achieved and stress of 0.17 MPa in in-plane loading. The stress, deformation and volume of the optimized model is shown below. Stress is in MPa and displacement in mm.

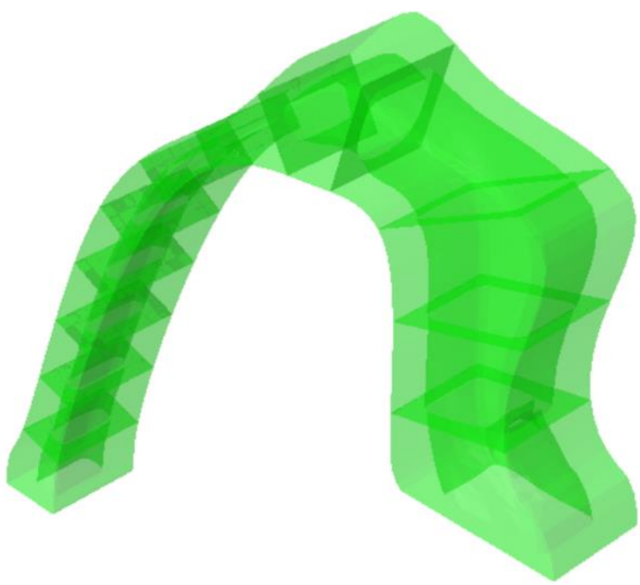

Figure 34: Model after optimization

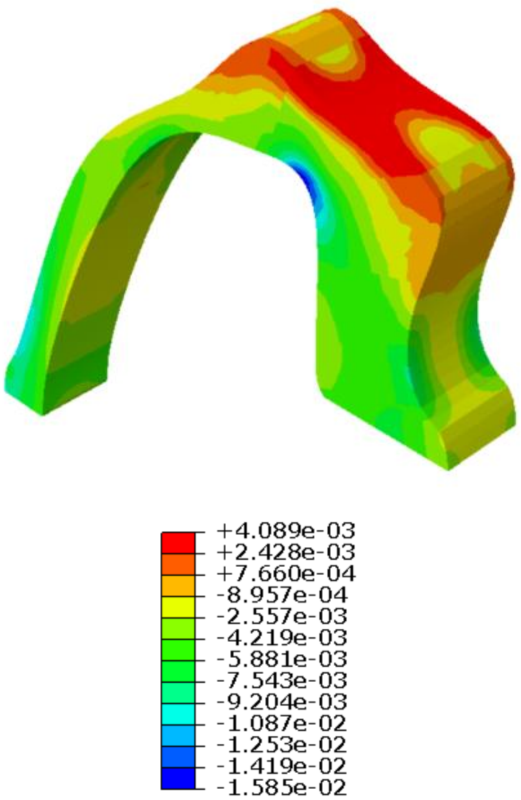

Figure 35: Stresses (MPa)

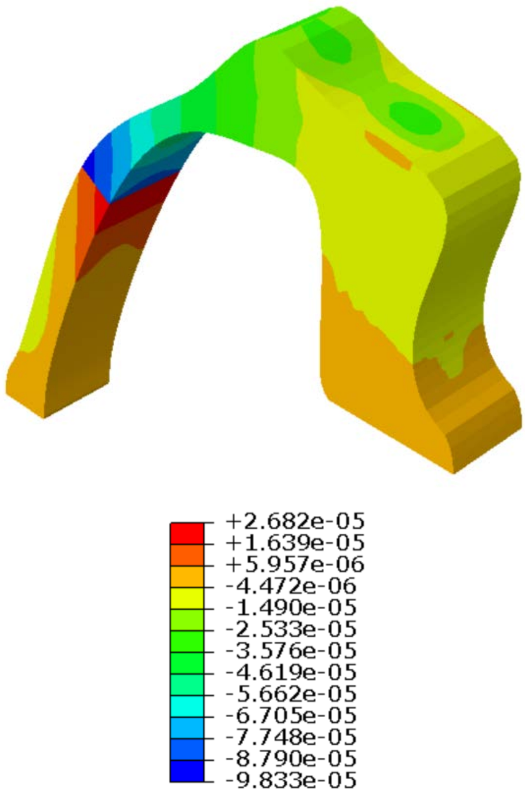

Figure 36: Displacements (mm)

In the case of an out of plane seismic activity the reduction of volume of the optimized model is 48.8 percent of the original and stresses are 0.22 MPa. The stress, deformation and volume of the optimized model is shown in the following figures. Stress is in MPa and displacement in mm.

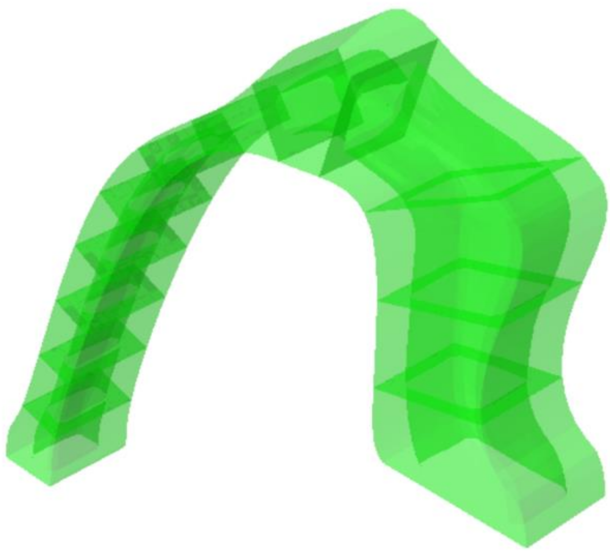

Figure 37: Model after optimization

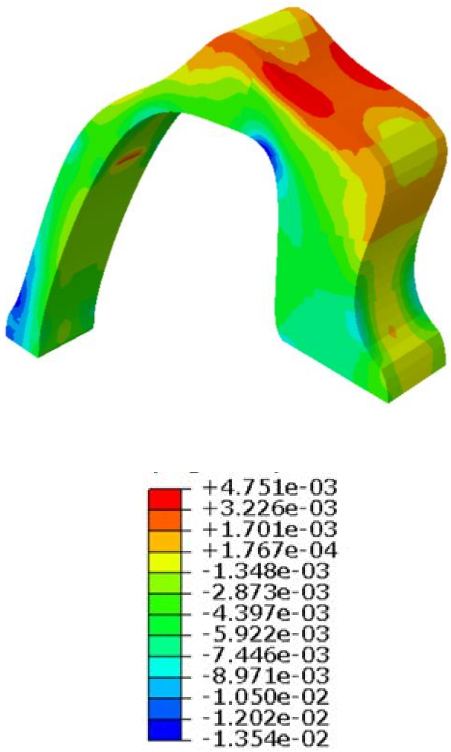

Figure 38: Stresses (MPa)

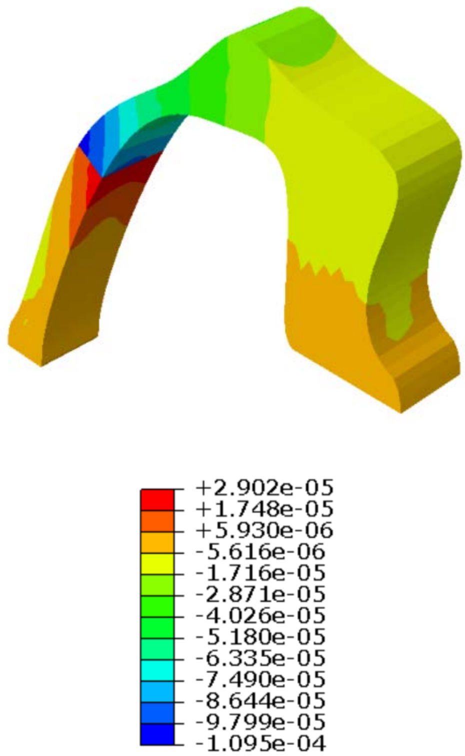

Figure 39: Displacements (mm)

In the third model for self weight loads the stress constraint is the same as in the second case, namely from 0 to -40 MPa the reduction of volume is 40 percent to the initial volume. Thus, the reduction of the volume to 64.8 percent was achieved, i.e., the construction now has a volume of 35.2 percent of the original. Stresses remain the same.

Figure 40: Model after optimization

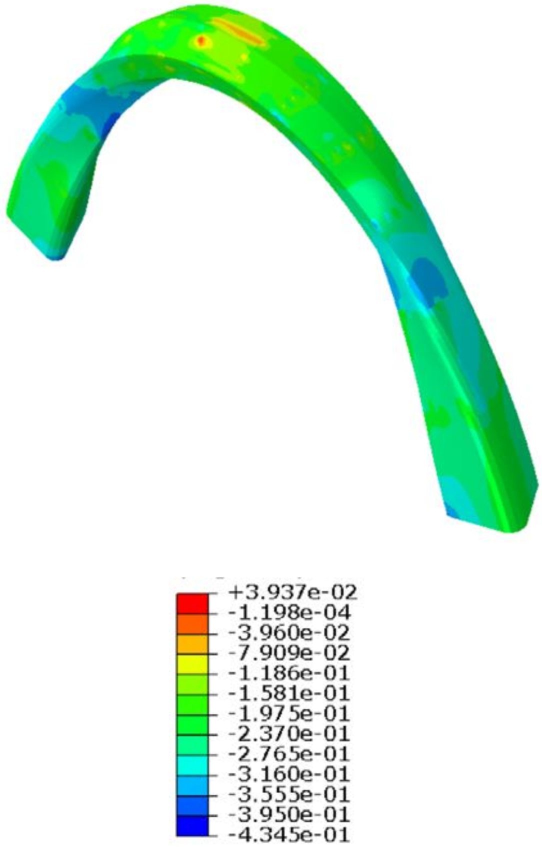

Figure 41: Stresses (MPa)

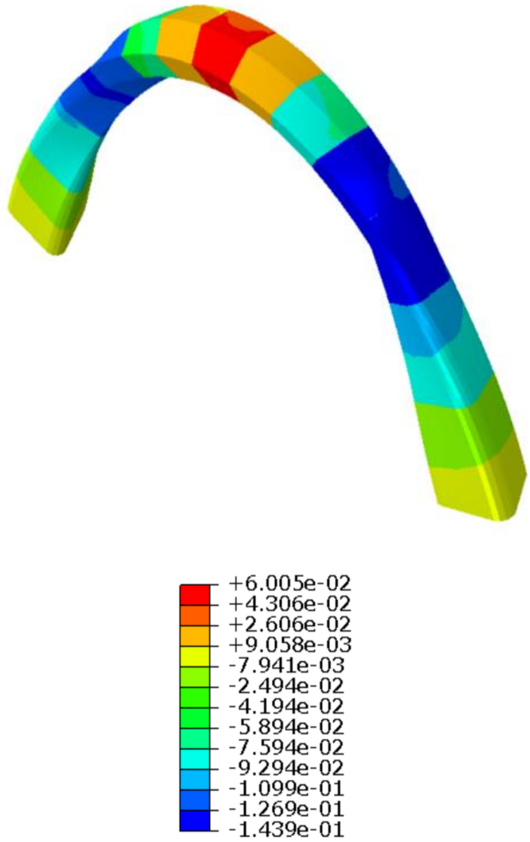

Figure 42: Displacements (mm)

For an in-plane seismic action the reduction of volume is set to 40 of the original percent and stresses from 0 to -40 MPa . A reduction of the original volume was achieved with stress at 2.5 MPa. Volume cannot be further reduced as the interface becomes to small and slips.

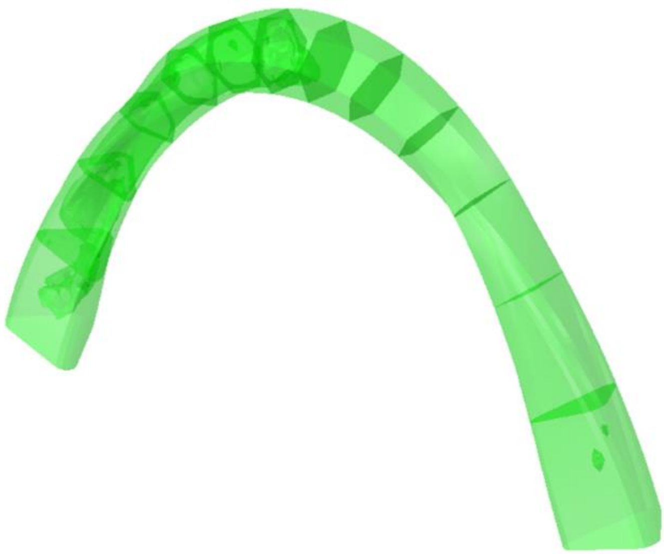

Figure 43: Model after optimization

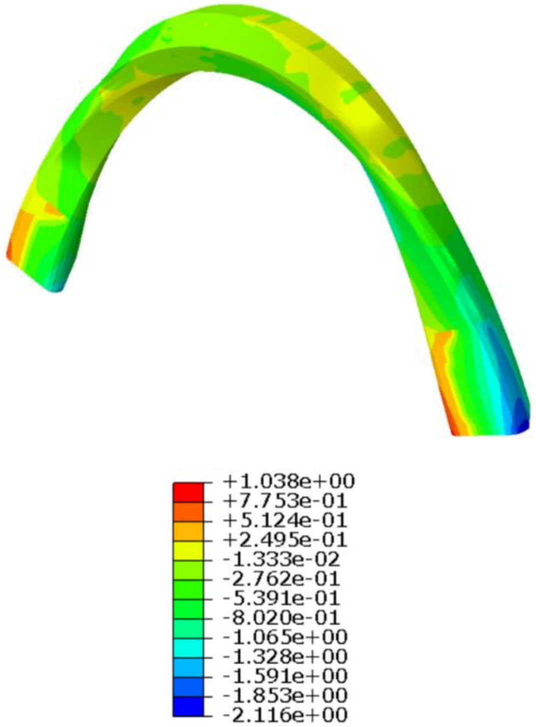

Figure 44: Stresses (MPa)

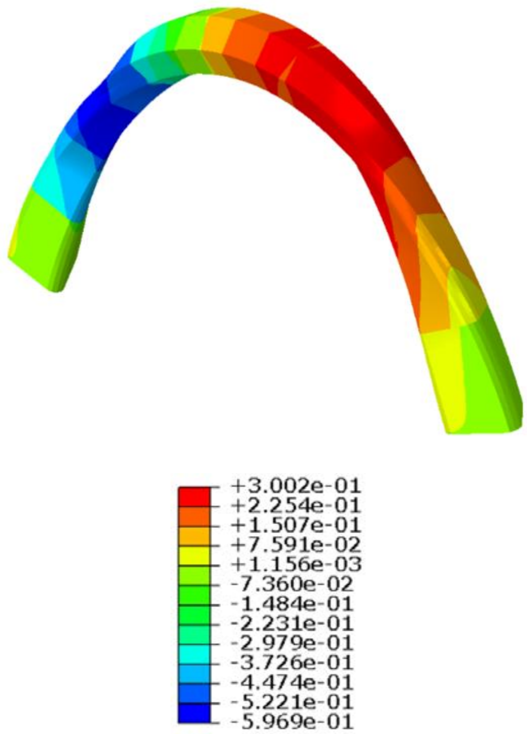

Figure 45: Displacements (mm)

The optimization of the third construction for an out of plane seismic action is important. When the construction was analyzed without a reduction of volume the stresses were larger. With a reduction of volume of the construction and therefore the mass the inertial moments on the construction are smaller. A reduction of 64.9 percent of the original was achieves and stress is at 0.7 MPa. The stress, deformation and volume of the optimized construction is. Stress is in MPa and displacement in mm.

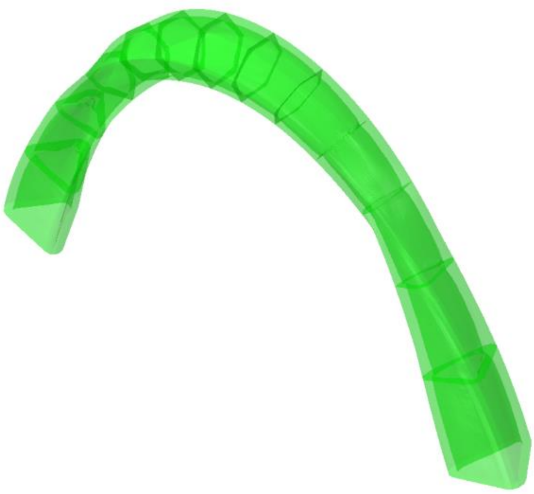

Figure 46: Model after optimization

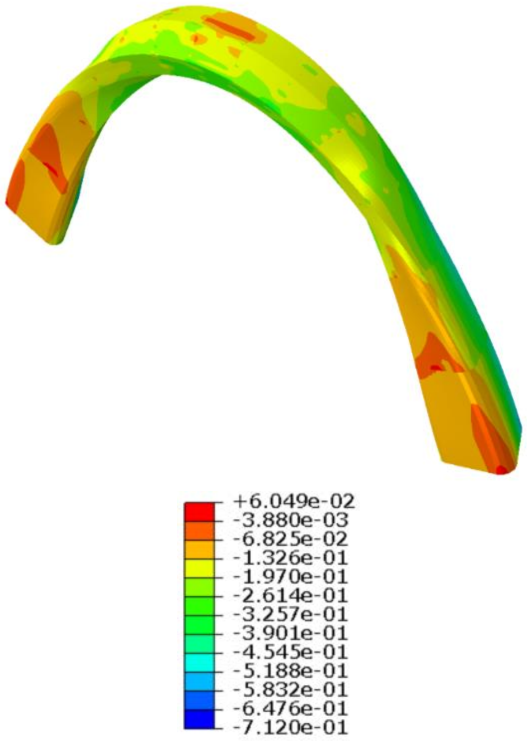

Figure 47: Stresses (MPa)

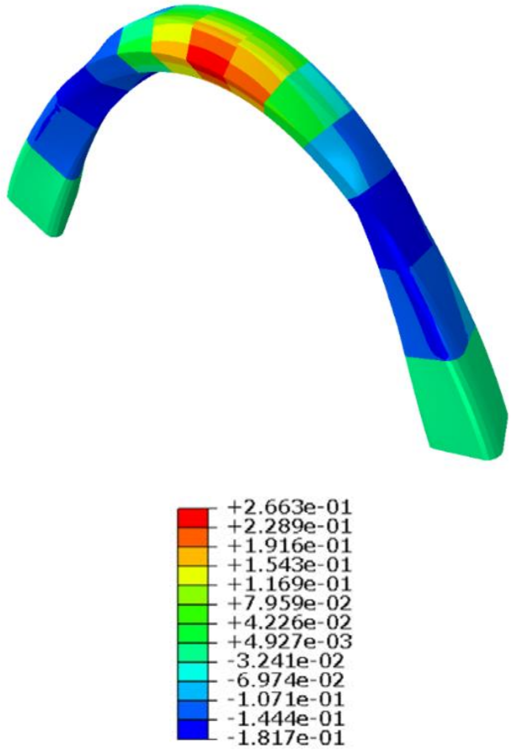

Figure 48: Displacements (mm)

4 DISCUSSION

It is observed that a key role for the static adequacy of arched constructions is played between the friction between the voissoirs their strength as well as the load carrier geometry to be in such a way as mainly compressive stress appears on the interfaces. The interface area that has compressive stresses named active area. In all three cases there are no static inadequacies for gravitational forces.

When only gravitational forces are applied, we have a larger active surface as the distribution of compressive stress in the interfaces of the individual pieces possesses the entire surface area. From the definition of stress, it is understood that the larger the area the force is exerted the smaller the stress, therefore the stresses do not exceed the maximum design stress of the material, and in that way, there is no stress concentration created. Therefore, there is no form of failure that can lead to collapse. The shear stresses between the voussoirs of the first and third structures do not exceed anywhere the critical stress, so there are no large slips observed. In the second structure, a large amount of slip was observed between the voussoirs therefore the maximum shear friction stresses were exceeded between them a connecting mortar was used for initial consistency.

In the case of seismic activity two out of the three constructions do not fail. It is important to mention at this point that there must be approximately equal surfaces between the voussoirs so that there are no sensitive areas created, that are dangerous for the concentration of stresses where the material strength can be overcome or in a possible earthquake the pieces can slip as happens in the second construction.

In the third structure, large slips are observed between the voussoirs when the earthquake hits out of the plane and therefore the spectral acceleration is reduced. In a seismic activity stresses between the individual pieces must be thoroughly checked as it is very likely for stress concentrations to appear at some points of the pieces of the structures near the interfaces. In all three constructions the given loads do not exceed at any point the maximum allowable stress. However in all structures it is observed that the active surface between the pieces is significantly reduced.

From the three constructions that were analyzed above we conclude that we have several advantages. The most important is the reduction in volume and thus the reduction of the material and the cost reduction of the construction and the stresses. This is observed mainly in the optimizations for gravitational loads.

An other important characteristic which is observed mainly by the topology optimization in seismic loads is that by reducing the volume of the constructions its mass is also reduced and so the best seismic performance is achieved. A characteristic example is the third construction where the stresses are drastically reduced in the optimized construction compared to the un-optimized one, something that is seen to a lesser extent in the first construction.

As it is observed it is crucial to check the seismic behavior as a change in the distribution of interface stresses is observed leading to a reduction of the active surface between the voussoirs. The material that is removed is removed in such away so that we have the optimal behavior in the interfaces i.e., either the optimal stress distribution or the optimal displacement as far as slip is concerned. Consequently, even though we have the same percentage of removed volume on the same construction it is removed from different areas for different loads.

5 CONCLUSIONS

The use of arched structures was mainly used in the past, but it is a construction method that can help in the constructions of the future. Arched structures can help in the construction of buildings or parts of buildings that will be printed in three-dimensional pieces. These pieces will be optimized to achieve the reduction of their volume and then will be assembled in the construction site. With this way of construction, the construction will be simplified, and the process will be automated, since the physical presence of man will not be needed anywhere. Finally, the volume of all three constructions is drastically reduced, resulting in reduced environmental footprint and lower construction costs due to fewer materials and due to the reduction of working hours owing to the simplification of construction. The next Figure shows a staircase which has been designed with the method that all three constructions of this dissertation have been designed to give as an example of a construction whose design is the same as those of these arched structures.

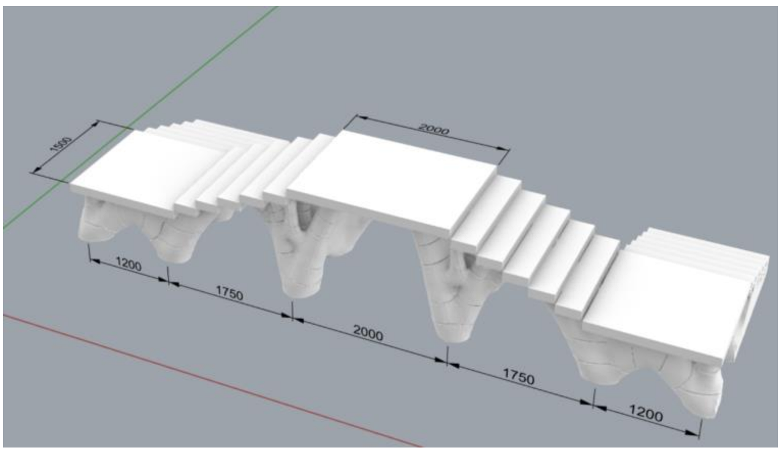

Figure 49: Staircase.

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